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Particle dark matter: A multimessenger endeavour

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Summary. — The search for dark matter (DM) as a new, yet undiscovered, particle is explored through a complex host of different signals, from collider to direct and indirect searches. A special focus is dedicated to the latter ones, covering the full electromagnetic spectrum (from radio to gamma-rays), charged cosmic-rays and neutrinos. The expected DM signals are by definition faint, but the possibility to exploit a wide-field investigation offers promising prospects. In this brief review, I summarize the state-of-the-art in the search for particle DM signals, exploring some new ideas that are emerging in the effort of the scientific community to understand the elusive nature of DM.

1. – Introduction

Unveiling the elusive nature of dark matter (DM) is one of the gold-rushes in cosmology and particle physics today.

In the last four decades, gravitational evidences for DM have been accumulated at the galactic, cluster and cosmological scales. Historically, the first solid hint for its existence came from rotation curves in spiral galaxies, *e.g.*, [1], although first claims date back to the 30's [2] and refer to cluster dynamics. On large scales, our understanding have recently experienced tremendous progresses, allowing to distinguish among many different cosmological models. As a cornerstone, the measurement of the power spectrum of cosmic microwave background (CMB) anisotropies led to a detailed determination of cosmological parameters [3]. It is in agreement with large scale structure (LSS) and Big Bang nucleosynthesis (BBN) data, and they all require the matter density in the Universe to be much larger than the baryonic density.

These gravitational evidences do not shed light on the microscopic properties of DM. On the other hand, the consistency of this scenario suggests collisionless and dissipationless DM, as in particular required by formation of galactic halos and by clusters merger

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dynamics (*e.g.*, the so-called Bullet cluster [4]). Moreover, the bottom-up hierarchy in structure formation points towards cold DM, *i.e.*, DM with non-relativistic velocity at the time when structures started to form.

Making the conservative assumptions that the DM is stable and was in thermal equilibrium with the plasma of the primordial Universe, its relic density can be expressed through (*e.g.*, [5])

$$(1) \quad \Omega_{DM} h^2 \simeq \frac{3 \cdot 10^{-27} \text{ cm}^3 \text{ s}^{-1}}{\langle \sigma_a v \rangle},$$

where $\langle \sigma_a v \rangle$ is the thermally averaged annihilation rate. Equation (1) implies that DM particles with annihilation cross section mediated by weak interactions (and mass $m_{DM} \sim \mathcal{O}(100 \text{ GeV})$) are naturally produced with the correct relic density. This is the so-called “WIMP miracle” and the appeal of the weakly interacting massive particle (WIMP) class of DM candidates mostly stems from it. Theories beyond the standard model (SM) of particle physics can easily account for WIMPs. Indeed, one of their foundation motivations relies on addressing electro-weak (EW) symmetry breaking issues of the SM, so they naturally introduce particles at EW scale and with weak couplings. Examples include lightest supersymmetric particles in Supersymmetry [6], and Kaluza-Klein states in flat and warped extra-dimension models (*e.g.*, [7]). Moreover, weak couplings ensure that the DM interaction with standard matter is sizable making the DM detection in current and near future experiments possible.

In the rest of the review, I will keep the discussion general, describing observational prospects for DM candidates with mass in the GeV-TeV regime and cross-sections around the weak case.

2. – Collider and direct DM searches in a nutshell

The production of WIMPs at collider stems from the process: $p_{SM} + p_{SM} \rightarrow \chi_{DM} + \chi_{DM} + \text{“some } p_{SM}\text{”}$, where p_{SM} is a particle of the SM. For $m_{DM} \leq \text{few TeV}$, DM particles χ_{DM} can be produced at LHC. On the other hand, the weak interaction makes them invisible and WIMPs can be only detected as missing energy events. This track, plus the signature of “some p_{SM} ”, has to be disentangled from the SM background. Since missing transverse energy is common to most exotic physics beyond the SM, the DM signal has to be combined with other observables (*e.g.*, DM cosmological relic density, or direct and indirect searches) to lead to a robust DM discovery. Tests of the particle physics framework in which the DM candidate can be embedded provide other indirect cross-checks for DM interpretations. So far, experiments at LHC have found no clear evidence of a WIMP signal. On the other hand, with Run-2, they are currently entering in a phase offering the possibility to explore relevant benchmark WIMP models. For a review of the adopted techniques, see [8]. The topic is extensively covered in other contributions of this book.

As mentioned before, the DM is not only a cosmological issue, but rather it is postulated down to galactic scales and a significant WIMP population is expected at our location in the Milky Way. Because of the WIMP miracle, and using crossing symmetry, scatterings of WIMPs with ordinary matter proceed through weak interactions and the direct detection strategy consists in recording the recoil energy of target atomic nuclei after being scattered by a WIMP. The nuclear recoil can be measured by detecting the

induced light, charge or phonons through scintillation, ionization and lattice heat. Current direct detection experiments exploit one or combine two of such techniques. We refer the reader to other contributions on direct detection in this book for details on a few ongoing experiments.

From the theoretical side, recently, there has been a significant effort in the community to go beyond the simplest paradigm (contact scalar interactions) using a full set of effective operators for the DM-nucleus scattering [9]. This suggested a variety of possible interactions and, in turn, of possible different experimental responses, depending on the detector properties. The search for characteristic WIMP signatures (as, *e.g.*, annual/diurnal modulation and directionality) is therefore crucial to have model-independent evidences.

3. – Indirect DM searches

Indirect detection strategies involve signals associated to fluxes of particles originated from WIMP annihilations or decays in astrophysical structures. Antimatter (including positrons, antiprotons, and antideuterium), photons (from gamma-ray prompt production and multi-wavelength radiative emissions), and neutrinos are the most promising channels currently investigated.

Antimatter. – The local positron fraction data show a sharp raise at high-energy, confirmed by different experiments [10]. This feature suggests the presence of a nearby (within few kpc) source of positrons. A WIMP interpretation is viable for heavy ($\mathcal{O}(\text{TeV})$ mass) and leptophilic (*i.e.* with dominant branching ratio of annihilation into leptons) DM, although constrained by the γ -ray bounds. Moreover, more mundane interpretations, such as, *e.g.*, pulsar emission, are found to be able to fit the data.

The antiproton fraction has been recently measured by the AMS-02 collaboration [11]. A possible hardening above 100 GeV has triggered some speculations concerning a WIMP contribution. At present, however, data are compatible with a pure secondary production.

The antideuteron channel is a promising discovery tool for the future, since the cosmic-ray background is expected to be rather low [12]. On the other hand, both AMS-02 and GAPS have limited detection prospects for benchmark WIMP models.

Gamma-rays. – The currently more quoted γ -ray targets for WIMP detection and constraints are, respectively, the Galactic Center (GC) and the dwarf spheroidal galaxies.

Since the γ -ray signal scales with the square of the WIMP density and the DM density is found to be maximal at the center of astrophysical systems, the GC is one of the prime targets for WIMP searches. Recently, a residual of γ -ray emission compatible with a WIMP interpretation has been found at the GC after subtracting some models for the expected diffuse emission [13]. On the other hand, the GC is a very rich and complex region, and the awkwardness of the modeling makes difficult to hold up strong statements.

Dwarf spheroidal (dSph) galaxies have been recognized as optimal laboratories for indirect DM searches. They are not only the closest (other than the Galaxy itself) and most DM dominated objects in the local Universe, but they are also the faintest and most metal-poor stellar systems known (see, *e.g.*, ref. [14] for a recent review), which implies low expected non-thermal emission. No evidence of diffuse signal has been

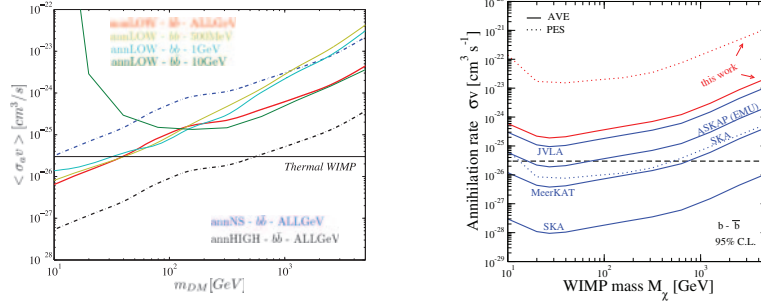


Fig. 1. – 95% upper bounds on the DM annihilation rate $\langle \sigma_a v \rangle$ as a function of the DM mass. Left panel: Bounds derived from the cross-correlation of Fermi-LAT maps with galaxy catalogs. See ref. [25] for details. Right panel: Constraints from radio signals induced by WIMPs annihilating into $b\bar{b}$ in dSphs. See ref. [29] for details.

obtained so far at any relevant frequency and this allowed to set upper limits on the DM annihilation/decay rate.

The more stringent bounds come from the Fermi-LAT Collaboration based on 6-year observations and a joint likelihood analysis of 15 dSphs [15]. At 95% CL and assuming an NFW dark matter distribution, the bounds constrain the “thermal” annihilation rate $\langle \sigma_a v \rangle = 3 \cdot 10^{-26} \text{ cm}^3/\text{s}$ for masses $\leq 100 \text{ GeV}$ in the cases of $\tau^+\tau^-$ and hadronic final states (while being an order of magnitude weaker for lighter leptonic final states).

The dSphs are typically considered as a “clean” target, meaning that they have low uncertainties related to the astrophysical properties of their DM and baryonic content. On the other hand, it has been shown [16] that the uncertainty in the estimate of the DM density for the ultra-faint dSphs are typically grossly underestimated. In turn, the WIMP bounds can be significantly relaxed.

New directions. –

- Cross-correlation with gravitational tracers

Even if DM halos are too faint to be individually detected in gamma-rays, they form the most numerous population in the Universe. The extragalactic DM “cumulative” signal or its spatial coherence might be observable. To increase the sensitivity to non-gravitational DM sources one needs to isolate the annihilation/decay signal produced at low redshift. An effective way to filter out any signal that is not associated to DM-dominated structures or that is originated at high redshift is to cross-correlate the radiation field with bona fide low-redshift DM tracers [17-26]. Both galaxy catalogs and lensing surveys have been discussed as the tool providing the gravitational field for the cross-correlation.

This novel method, proposed in [17], can be extremely promising, also in light of forthcoming cosmological surveys, such as the Dark Energy Survey and Euclid. Most stringent current bounds derived with this technique are shown in fig. 1(a), taken from ref. [25].

- DSph galaxies can exhibit synchrotron emission from electrons and positrons injected by WIMP annihilations, if an ambient magnetic field is present. Very recently, radio campaigns using the Australia Telescope Compact Array [27-29]

and the Green Bank single-dish radio telescope [30,31] have been conducted targeting such signal. No significant evidence for an extended emission was found. Bounds from ref. [29] are reported in fig. 1(b). On the other hand, fig. 1(b) shows also that the SKA and its precursor will be able to progressively probe a signal from WIMP scenarios with “thermal” annihilation rate and masses up to few TeV, irrespective of astrophysical assumptions.

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